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Design of Fast Connected Components Hardware

by

Xue Dong Yang

Technical Report No. 353

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Design of Fast Connected Components Hardware

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Abstract

The intensive use of the connected components algorithm in image analysis and robot vision calls for a very fast implementation of such algorithm suitable for real-time applications. This paper presents a hardware design implementing the algorithm due to Schwartz, Sharir, and Siegel[8]. A prototype board, without using special VLSI chips, had been constructed in Robotics Research Lab of Courant Institute. It can compute the connected components of a 512×512 binary image in few video frame times (about 300 ms). A real-time version (video speed) in VLSI is proposed.

1. Introduction

The labeling of connected components of a binary image is a fundamental problem in image analysis. An early method was developed by Rosenfeld and Pfaltz [7] in 1966; it uses a pair of arrays, one containing the current region label and the other containing its smallest equivalent label. This algorithm processes the image from top to bottom to compute label equivalences, storing the result in the arrays. A second pass reassigns each label to its smallest equivalent label. Lumia, Shapiro, and Zuniga [3] improved the previous method by using a very short equivalence table, which needs to cover only one line. Schwartz, Sharir, and Siegel [8] present a method which uses bracket marking to associate equivalent groups. This method enables one to compute the component numbers for each pixel on the fly, by using an relative small auxiliary 'bracket table'. More interestingly, this algorithm uses only simple form of pushdown-stacks, making high-speed hardware realization possible. In addition to the above mentioned sequential algorithms, Shiloach and Vishkin [9] present a logarithmic-time connected components algorithm known for massively parallel computing systems (e.g. 1 processor per pixel) connected in shuffle-exchange or other similar pattern.

In this paper, we present a hardware implementation of the algorithm due to Schwartz, Sharir, and Siegel[8]. In the following sections, data structures and algorithm are described in detail. Then the hardware design realizing the algorithm is presented. A prototype Connected Components Board, which does not use any specially designed VLSI chips, has been constructed at Robotics Research Lab. of Courant Institute, NYU. It can label the connected components of a 512×512 binary image in just a few video-frame times (about 300 ms). Real-time computation (i.e. video speed) can be achieved without significant redesigning by pipelining the two major computing components of the board. For a connected components algorithm to be suitable for intensive use in real-time image processing and robot vision

applications, it must allow for a very fast implementation. In the last section we discuss this enhancement and outline a possible VLSI implementation of the algorithm.

2. The Algorithm and Its Implementation

The algorithm that we have implemented was first presented in [8]. For the sake of completeness, a description of the algorithm, and the details which are relevant to its hardware implementation are given below. First, we review key definitions as follows:

Definition 1: Let R_p be an image row, ($1 \leq p \leq m$).

(a) A run in R_p is a sequence of 1-pixels (i.e. pixels with gray value 1) of R_p bounded on both sides by 0-pixel (For simplicity, we add two additional 0-pixels to the left and right-end of each row of the image, respectively).

(b) The lower semi-image I_p consists of the union of all rows R_j , $p \leq j \leq m$.

(c) G_p is defined to be the partition of the set of runs in R_p , for which two runs are in the same partition group $g \in G_p$, iff they belong to the same connected component of the lower semi-image I_p .

The algorithm consists of two passes. *Pass 1* sweeps through the rows from bottom to top, during which the groups in G_p are calculated inductively from the knowledge of R_{p+1} by a simple updating rule. *Pass 2* sweeps from top to bottom to assign component numbers to each pixel and outputs this symbolic image.

In each row, runs belonging to the same group are associated by a simple mechanism, called **bracket marking**, as follows:

Definition 2: We define four symbols '[', ']', '[]', and '[]['.

(a) If r is the leftmost (resp. rightmost) run in its group g , it is assigned marking [(resp.)].

(b) If r is both leftmost and rightmost run in g , i.e. g consists of a single run r , then r is assigned the marking [].

(c) If r lies between the leftmost and rightmost run in its group, it is assigned the marking []['.

An example is given in Fig 2.1, where a bracket marking is shown for seven runs in R_p numbered from right to left. These seven runs are divided into three groups - (7,4,3,1), (6,5), and (2). It is shown in [8] that the bracket sequence associated with row R_p is **properly nested**, i.e. each right bracket is matched to an associated left bracket and vice versa. Hence, the groups into which we divided the set of all runs in R_p can be reconstructed from the bracket sequence associated with R_p .

2.1 Pass 1

The goal of *pass 1* is to calculate a bracket marking for each row by sweeping from bottom to top, and to store it in a bracket table (to be accessed in *pass 2*). For this we want a rule telling us how to calculate the bracket marking for the row R_p

Figure 2.1 An example of bracket marking assignment

given the same information for R_{p+1} . The key observation is that any two runs in row R_p will be in a group $g \in G_p$ iff there are some runs in $g' \in G_{p+1}$ whose index set has a nonempty intersection with the index sets of the two runs in R_p . Intuitively, those runs in row R_p which are linked together by a chain in the semi-image I_p belong to the same group. The algorithm scans two rows, R_p and R_{p+1} , simultaneously from right to left. Two pushdown stacks, *stack1*, and *stack2*, are used in *pass 1*. *Stack1* is used for tracing the group relationship represented by the bracket sequence in R_{p+1} as following:

- (a) If a run with ']' is encountered, we push a unmarked symbol onto *stack1*;
- (b) If a run with '[' is encountered, we neither push nor pop;
- (c) If a run with '[' is encountered, we pop the top entry off *stack1* at the end of this run;
- (d) If a run with '[' is encountered, we push an unmarked symbol onto *stack1* at the beginning of the run, and pop *stack1* at the end of the run.

When we are within a run in R_{p+1} during scan, if we encounter a run in R_p , then we mark the symbol on the top of *stack1*, which indicates that the current group in R_{p+1} has touched some run in R_p . When a run in R_p is encountered and we are within a run in R_{p+1} with a ']' or '[' marking, we look at the top entry of *stack1* to see if it is marked, i.e. to see if the current group in R_{p+1} already touched previously some run in R_p . If so, the current encountered run in R_p is linked to some run to its right in the same row through a path below R_p .

Stack2 is used for maintaining the group information about the row R_p during the scan. Assume we number each run in row R_p from right to left starting from 1, as an example shown in Fig. 2.1. Each entry in *stack2* is a pair of integers, representing the right-most and left-most runs of each group known to the point we have reached during scan. This group boundary information is updated according to the new knowledge we gain about each group as the scan continues. Given the way that we scan a row from right to left, the connectivity of runs in row R_p through links in the semi-image I_{p+1} can be classified into three basic cases as follows (refer to Fig. 2.2):

- (a) Several runs may be linked by a simple chain;
- (b) A cluster of links (or arcs) may be bound together on its right end by a single run in row R_p ;
- (c) A cluster of links (or arcs) may be tied together on its left end by a single run in row R_p .

Figure 2.2 Basic cases of connectivity in semi-image I_p :
 (a) simple chain; (b) a cluster of links is bound at right end;
 (c) a cluster links is bound at left end.

The general case can be decomposed recursively into these three elementary cases by recursively considering a subset of consecutive runs in a group as a "single run". For example in Fig. 2.1, if we consider runs 4 and 3 as a "single run" denoted by 4-3, the connectivity between 7, 4-3, and 1 falls into the elementary case (c). Our algorithm handles the connectivity problem from inner level to outer level recursively. Thus, at any time, we only have to deal with one of the three elementary cases defined above; however a run could be a simple run or a virtual "single run".

2.1.1 Manipulation of Stack 2 Information

The condition for beginning a new group can be easily checked locally. When we encounter a new run in row R_p , we check if it makes contact with any run in row R_{p+1} . If it does not, we know that it is the start of a new group containing one run only. On the other hand, if it does make contact with some runs in R_{p+1} the right most of which has a ']' marking, we assume temporarily that a new group starts. (We say 'temporarily' here since initially no link connects the current run in R_p to a run to its right on same row. However this new run might link to some run to its right indirectly through several arcs. For example in Fig. 2.2(c), run 2 links indirectly to run 1 through two arcs.)

Case (a)

In case (a) of Fig. 2.2, we have entry [1,1] on *stack2* after reaching run 1, which means the left and right bound of the current group are 1 and 1 respectively. The left bound expands to 2 after run 2, resulting in the top stack entry [1,1] being updated to [2,1]. It is then updated to [3,1] when run 3 is reached, after which it is popped off *stack2* since a group is finished. So in case (a), the group always expands its left bound.

Case (b)

The situation in case (b) of Fig. 2.2 is slightly more complicated. We have [1,1] on *stack2* after run 1. (Remember that we have two marked entries on *stack1* after run 1 in row R_p since it touched two runs in row R_{p+1} both of which have ']' brackets.)

After run 2, the top entry on *stack2* becomes [2,1] and the top entry on *stack1* was popped. At this point we do not know whether or not to pop the top entry on *stack2*. While it is possible, using only local information to determine the start of a new group, this is not the case for determining the end of the current group. The fact that a run has no more arcs linking it leftwards does not necessarily mean that the end of this group has been reached. (Note that run 2 is further linked to run 3 through an indirect path.)

To handle this situation, we introduce an auxiliary field in *stack1*'s entry to indicate if the arc associated with a ']' marking in that entry is the outermost (or lowest) arc. For example, we say arc A is the lowest among the cluster of arcs bounded by run 1 in row R_p in (b) of Fig.2.2. The auxiliary bit can be easily set as following. During a run in row R_p , if one or more entries have to be pushed onto *stack1*, the auxiliary field in the first pushed entry is set to TRUE and the auxiliary fields in all other entries are set to FALSE. If the auxiliary field in the entry just popped off *stack1* is FALSE, we know the arc (or link) just ended is not the outermost one (lowest), i.e. there is an arc belonging to the same group enclosing this finished arc, so we don't pop the entry off *stack2* because we don't know if the current group in row R_p is finished yet. After reaching run 3 in row R_p , the left bound of current group is expanded to 3, and the top entry on *stack2* is changed from [2,1] to [3,1]. When the entry on *stack1* is popped off, we see that the auxiliary field is TRUE. So, we can confidently pop the top entry on *stack2* off this time because we know that there is no further arc linking this group to any run to its left.

Case (c)

A situation symmetrical to case (b) occurs in case (c). After reaching run 1, we have one entry, [1,1], on *stack2*. Note that at the moment after reaching run 2, it is impossible to know that this run is actually linked to run 1 through an indirect path. So, we have a second entry, [2,2], on top of *stack2*. After point x_1 in run 3 is reached, the top entry of *stack2* is updated from [2,2] to [3,2]. When we reach point x_2 we find that two arcs are bound together. So, the two top entries on *stack2* are merged into one in such a way that the new left bound is the left bound of first entry on *stack2* and the new right bound is the right bound of the second entry of *stack2*, resulting a [3,1] on *stack2*. These operations can be performed in two steps: (1) pop *stack2*; (2) modify the left bound of top entry by the left bound of just popped entry. In this example, we pop [3,2] off *stack1* first; then change the left field of top entry - [1,1] to 3 and get [3,1] as the new top on *stack1*.

2.1.2 Bracket Table

The bracket marking can be effectively encoded by a two-bit binary number as shown in Table 2.1. The bracket information calculated during *pass 1* is stored in a memory of $512 \times 256 \times 2$ bits, called the *brackets table*. This table is indexed by two

Table 2.1 Bracket Marking Encode Definitions

Bracket Marking	Left Bit	Right Bit
[]	0	0
[	0	1
]	1	0
][	1	1

row counters, *row_count1* and *row_count2*, and two column counters, *run_count1* and *run_count2*. *Row_count1* and *run_count1* are combined to access brackets in row R_p , and *row_count2* and *run_count2* for those in row R_{p+1} . Each entry in the table has two 1-bit fields, both of which are initialized to zero. *Run_counts* are set to zero at the beginning of a row sweep and incremented by 1 every time a new run started.

Now we show how the bracket table can be updated efficiently as groups grow during scan. There are only two types of group-expanding operations: (a) the left boundary of the current group expands to include the current scanned run; (b) the two top most groups on *stack2* are merged together. To do each of these operations in constant time, we must be able to directly index correct columns in a row of the bracket table. The index of the current scanning run is provided by *run_count1* for row R_p and *run_count2* for row R_{p+1} . The boundaries of all non-ended groups are maintained in *stack2* in a proper nested order with the current group on the top. Thus, the updating of bracket table's entry in every possible case can be done in constant time. By the end of *pass 1*, we get a complete bracket marking for every run of the binary image stored in the bracket table.

2.2 Pass 2

In *pass 1* we have only solved the connectivity problem for runs in each row that connect through some links below that row. However, the connectivity between those runs in a row which are linked together only through some arcs above that row can not be found in this bottom-to-top sweep. A second pass sweeping in the opposite direction is necessary to solve the connected components problem completely.

Pass 2 is much simpler than *pass 1*. On each row, two sweeps are used. The first sweep scans the pixels in two consecutive rows, R_{p-1} and R_p , simultaneously from right to left. The second sweep scans row R_p from left to right only. We still use two stacks, *stack3* and *stack4*, but they play slightly different roles to the two stacks used in *pass 1*. *Stack3* is used to trace the group information in row R_p , and *stack4* saves the component number assigned to each group in row R_p . A circular queue is used for temporarily storing component numbers corresponding to each run in row R_{p-1} with the right-most run at the head of the queue.

The first sweep induces the component number already assigned to runs in row R_{p-1} to the runs in row R_p to which they are connected, and allocates a new component number to each new group emerged in row R_p .

When a run with ']' bracket is encountered in row R_p , which means the start of a

new group has been found, we push a *NULL* onto *stack3*. On the other hand, when a run is encountered in row R_{p-1} , we remove the entry at the tail of the queue which contains the component number corresponding to this run. Then if the current group of row R_p connects with any run in row R_{p-1} and the top of *stack3* is still *NULL*, we replace the top of the *stack3* by the entry most recently removed from the queue. When a run with a '[' bracket is encountered in row R_p , which indicates the current group has ended, we pop the top entry from *stack3*. If this popped element is not *NULL*, it is pushed onto *stack4*; otherwise, a new component number is allocated and is pushed onto *stack4*. At the end of sweep 1, we have the component numbers for each groups of row R_p in *stack4* with the last ended group's on the top.

The second sweep scans row R_p only, from left to right. When a run with '[' bracket is encountered, we pop its component number from *stack4* and push it onto *stack3*. The component number of a group on *stack3* is popped off at the end of the group's right-most run which must have a ']' bracket. Each pixel scanned is checked to see if it is white. If it is, then the background component number is output. Otherwise it is within a run, so we output the content on the top of *stack3* which is the component number of current group.

The full algorithm written in C Programming Language is given in Appendix A.

3. Hardware Design

In section 2, we have shown that all operations involved in the computation are

Figure 3.1 Block Diagram of Connected Component Board

simple and can be classified as follows:

- (a) Simple variable assignment (register transfer).
- (b) Indexed memory access (e.g. bracket table read/write).
- (c) Push stack, pop stack, or modify the top of stack.
- (d) Insert queue and delete queue.

It should, and does indeed, have a straightforward implementation in hardware.

The goal of the first prototype connected components board designed was to implement the algorithm described in section 2 in standard MSI or LSI chips without involving special VLSI chip design, and the computation on a 512×512 binary image can be accomplished in few video-frame times. Real-time implementation and VLSI design are discussed in the last section of this paper.

The design is carried out in a systematic way. We start by specifying modular units and connections between them. Then the data structure and functions performed in each module are precisely described by a number of processes written in a special microparallel system hardware design language (see Appendix B). Processes are then mapped into circuits by several regular rules. Our explanation concentrates on the architecture of the hardware. The low level schematic design can be found in [10].

The block diagram of the connected component board is shown in Fig. 3.1. There are five major components:

- (1) Pass 1 processor.
- (2) Pass 2 processor.
- (3) Image buffer.
- (4) Bracket table.
- (5) Input/Output interface.

In following, we examine each unit by describing the main data structure of the component along with its control structure.

3.1 Control Units

The computation of the algorithm is carried out by Pass 1 Processor and Pass 2 Processor. Both processors have very similar both data and control structures.

As can be seen in Fig. 3.1, Pass 1 processor contains a control unit, two stacks, and some local variables. The control unit coordinates the register transfers, stack operations, image buffer and bracket table accessings, according to the algorithm by issuing pulses to each component in an appropriate order. The control unit is implemented by a typical time sequential circuit or so called finite state machine. The structure of a finite state machine is given in Fig. 3.2 and its principle is explained in many digital logic design books, e.g. [11]. The output signals are control signals to each data components. The logical structure of control flow in the control unit of pass 1 is depicted in Fig.3.3.

There are two nested loops in the diagram, with the outer one iterating on rows and the inner one on columns. There are number of modules, so called processes, in Fig. 3.3. All processes are self-timed. Within each process some control signals are issued to data components to carry out manipulations. For example, when Pass1_Initialization process is activated, it sends control signals to set initial state for

Figure 3.2 Block diagram of finite state machine

Figure 3.3 The control unit of Pass 1 processor

pass 1 in various data components. The procedural descriptions of those processes can be found in Appendix B.

The control unit of the Pass 2 Processor has a similar structure as the Pass 1 Processor. Fig. 3.4 shows the logical control structure of the Pass 2 control unit. It contains three loops. The outer loop iterates on rows. The two inner loops are concatenated in serial. The first inner loop iterates on columns from right to left in a row; the second loop iterates in the opposite direction.

3.2 Data Components

3.2.1 Pushdown Stacks

The most important data structure here is the pushdown stack. The depth of each stack used is 256. A bi-directional shift-register seems the best element for implementing a pushdown stack. Since we couldn't find commercial shift-registers of such length, each stack in our design is constructed painfully from a piece of

Figure 3.4 The control unit of Pass 2 processor

Figure 3.5 The structure of pushdown stack

memory and a counter serving as the stack pointer as depicted in Fig. 3.5. Since the content of the top of a stack is frequently referenced as variables throughout the process, it is stored in a register rather than in memory. A push stack operation is performed in three steps:

- (1) Increment stack pointer by one.
- (2) Write the content of the register (the last top entry) into memory.
- (3) Gate the external value (the new top entry) into the register.

The pop operation is done in a similar manner. The updating of the top entry of a stack can be most efficiently done by just gating the external input to the register.

Note that since the stack operation needs more than one clock cycle, we have to latch the external input and control signals to the stack during the whole stack operation. Such latching circuits can be avoided if we design a stack in VLSI by just a simple array of bi-directional shift-register, since any operation needs only one cycle in this case.

3.2.2 Image Buffer

The image buffer is for storing a 512×512 1-bit binary image whose structure is shown in Fig. 3.6. Because of the relative low speed of memory access, we compact 8 bits into one word. So we need a total of 32K bytes memory. While reading pixels, a word is loaded from the memory into an 8-bits shift-register. Then individual bits can be get at the output pin of the shift-register sequentially. The advantage of this is that we have only one memory access for every eight pixels. In addition, the loading of a word from memory to shift-register could be overlapped with pixel computation.

As we mentioned in the algorithm, we need to scan two rows simultaneously.

Figure 3.6 The Structure of Image Buffer

Since the two rows that we want to read at the same time are always consecutive, one is an even numbered row and the other is odd numbered. This suggests a natural division of the image buffer into two ranks, one for even rows and one for odd rows, so we don't have conflicts in reading two consecutive rows at a time. The pixels from the current row and the previous row are obtained at out pins of shift-registers and latched in D-ff's.

Row_counter1, row_counter2, and column_counter provide the effective addresses for accessing two memory ranks through an address decoder.

3.2.3 Bracket Table

The bracket table is shown in Fig. 3.7. The bracket markings are encoded by two bits. These two bits are stored in two ranks of memory, $512 \times 256 \times 1$ bits each, for left- and right-bits respectively. The current bracket markings, read from the table, are latched in two D-ff's.

The row number is provided by row_counter1 and row_counter2 through a multiplexer. The column number is chosen from run_counter1, run_counter2, the top of *stack2* or last popped entry from *stack2*. An address decoder generates effective addresses for both ranks.

3.3 Input/Output Interface

Figure 3.7 The structure of bracket table

The general purpose handshaking interface we designed is flexible enough to be attached to a DMA controller, a parallel port or a serial port easily with a little additional logic.

The block diagram of the interface is shown in Fig. 3.8. There are two registers: (1) a status register; and (2) a command register. The meaning of each bit in the status register is given in Fig. 3.9(a) and in the command register in Fig. 3.9(b). The data bus has eight bit bi-directional lines. In the write-to-board mode, the data is supplied by an external device; and in read-from-board mode, the data bus is set

Figure 3.8 The block diagram of interface

* All bits are high active.

Figure 3.9 Bits assignment in status and command register

by the board. The data transfer direction is controlled by two input lines, PREAD and PWRITE, which are low active and exclusive. Another output line from the board, called READY, is an acknowledge signal to an external device to indicate that the buffer register of the board is empty in write-to-board mode, and full in read-from-board mode. The signal READY is high active.

The timing of those signals for I/O operations is given in [10].

4. Considerations on VLSI design and Real-time Applications

Since the connected components algorithm is such a fundamental procedure in image analysis and has more and more applications in robot vision, it is very attractive to implement this design on a VLSI chip, so it can be conveniently added to an image processing computer or general purpose system. Although we can simply map the whole circuit onto a chip and replace each logical gate by a corresponding cell of VLSI technique, it is not the best way to do it. The disadvantage of this approach is that the irregular structure of original design makes the physical layout in VLSI difficult. Many of the components can be implemented instead in a more efficient and much simpler style of VLSI.

For instance, a pushdown stack can be implemented by an array of bi-directional shift registers. It has several advantages: (a) it has a very regular pattern, so it is extremely simple to change the dimension of a stack; (b) a stack pointer is no longer necessary; (c) each of the three kinds of operations on a stack can be performed in just one cycle; (d) because of (c), the latching circuit for external inputs and control signal to the stack can be eliminated.

A control unit in VLSI is usually implemented in a more regular structure rather than a random logic design. The typical structure of a finite state machine in VLSI

Figure 4.1 Finite state machine

is shown in Fig. 4.1. The combinational logic network implements logical functions in the form of

$$Z = \sum_{j=1}^n a_{j_1} \cdot \dots \cdot a_{j_m}$$

It is not very difficult to write down the input to a register in our design as the function of other variables in the above form. So the full VLSI implementation is obviously possible.

More parallelism can be obtained at both the global and local level. For example, in the above design as Pass 1 processor is running, Pass 2 processor is idle. Globally, it is valuable to pipeline the two processors when we need to compute the input images continuously. A possible configuration is shown in Fig. 4.2. Instead of putting whole system on one chip, it can be naturally divided into four modules, namely the pass 1 processor, the pass 2 processor, the image buffer, and the bracket table. In Fig. 4.2 we have two image buffers and two bracket tables. When the pass 1 processor is working on set 1, the pass 2 processor works on set 2. At the end of a pass, the two processors can exchange image buffers and bracket tables. So when the pass 1 processor finishes one pass on image 1, the result is stored in bracket table 1. Then these data are passed to the pass 2 processor and at the same time the pass 1 processor starts working on the next incoming image with the other image buffer and bracket table. Data switching can be done trivially with multiplexers.

If the order of output sequence of a symbolic image is allowed to be reversed, we can reverse the sweeping directions of both pass 1 and pass 2. In such a case, the pass 1 processor doesn't have to wait until the entire image has been loaded into the image buffer. In other words, it can run during the image loading process. This, however, introduces the possibility of simultaneous accesses to the image buffer by the image loading process and the pass 1 computation process. So some additional mechanism, such as a semaphore, is needed to coordinate the processes.

Locally, some operations in each of the processes can be obviously performed during a single cycle without conflicts in the data path. Such parallelism can be

Figure 4.2 The configuration of a pipeline processor

easily achieved by broadcasting a control signal to more than one proper data components. This kind of parallelism has been realized in the many processes of our design.

As the speed of computation increases, data transfer will cause a bottleneck. It seems that regular DMA transfer in micro or mini systems would not be able to match the the computation speed. An ultra fast secondary bus directly connecting it to other system modulars is more preferable.

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Appendix.A

Connected Components Algorithm Implemented in C Programming Language

```

/* Constants and macro definitions */

#include      <stdio.h>
#include      <math.h>

#define MAXROW      512
#define MAXCOL      512
#define MAXRUN      (MAXCOL/2)
#define Qlen        (2*MAXRUN)

#define START_C      (!(_cpix)&&(cpix))
#define START_P      (!(_ppix)&&(ppix))
#define END_C        (!cpix)&&(!_cpix)
#define END_P        (!ppix)&&(!_ppix)
#define OVERLAP      ((cpix)&&(ppix))
#define IN_PRUN      (ppix)
#define IN_CRUN      (cpix)

#define BRKT         brkt[0]*2+brkt[1]
#define _BRKT        _brkt[0]*2+_brkt[1]
#define LEFT         1
#define RIGHT        2
#define CLOSE        0
#define MID          3

/* Global subroutine */
int      conncomps();

/*      Global Variables */

short  BrktL[MAXROW][MAXRUN]; /* left column of brackets table */
short  BrktR[MAXROW][MAXRUN]; /* right column of brackets table */
int     run_count1;           /* current run's number in current row */
int     run_count2;           /* current run's number in previous row */
int     brkt[2];              /* bracket marking associated with
                               the current run in previous row */
int     _brkt[2];             /* last content of brkt[] */

extern short  image[MAXROW+2][MAXCOL+2]; /* source image */
extern short  components[MAXROW][MAXCOL]; /* destination image */
int     colour[7]             /* codes for VICOM pseudo colours */
      = {0X120, 0X5A6, 0X240, 0X364, 0X6C8, 0X000, 0X486};
int     cpix,                 /* current pixel in current row */
      ppix,                   /* current pixel in previous row */
      _cpix,                  /* last pixel in current row */
      _ppix;                  /* last pixel in previous row */

```

```

Int    queue_count1,queue_count2;           /* components number queue pointers */
Int    component_No;                       /* next new identify number */

/* Main subroutine */

connected_conncomps()
{
    Int    row,col;

    /* initial brackets table */
    for (row=0; row < MAXROW; row++)
        for (col=0; col < MAXRUN; col++) {
            BrktL[row][col] = BrktR[row][col] = 0;
        }

    /* PASS 1: Scan from bottom to top to generate
       brackets marking for each run of each row */

    for (row=MAXROW; row>0; row--)
        Sweep_of_Pass1(row);

    /* PASS 2: Sacn from top to bottom to assign
       components ID# to each pixel of the image */

    component_No = 1;
    queue_count1 = queue_count2 = 0;
    for (row=1; row<=MAXROW; row++)
        Sweep_of_Pass2(row);
}

```

```

/*
    Scan row for PASS 1 to generate brackets marking
    for each run of the row scanned.
*/

Sweep_of_Pass1(i)
int    i;                                /* current scanned row number */
{
    short  stack1[MAXRUN][2];            /* stack1 is for tracking brackets in previous row.
                                           stack1[][0]=1, indicates the current group in
                                           previous row contacted one or more runs
                                           in current row;
                                           =0, otherwise.
                                           stack1[][1], auxilliary flag. */
    int     sp1;                          /* stack pointer for stack1 */
    int     popped1;                      /* last content of stack1[sp1][1] */

    short  stack2[MAXRUN][3];            /* stack2 is for maintaining the temporary boundaries
                                           of groups in current row.
                                           stack2[][0], right-most run of current group;
                                           stack2[][1], left-most run of current group;
                                           stack2[][2], auxilliary flag. */
    int     sp3;                          /* stack pointer for stack2 */
    int     popped2[3];                   /* last entry popped from stack2 */

    int     touch_p;                      /* =1, indicates the current run in current
                                           row already touched an run in previous row! */
    int     touch_c;                      /* current run in previous row already touched
                                           an run in current row */
    int     col;

    /* Initialization at beginning of a sweep */

    touch_p = touch_c = 0;
    sp1 = sp3 = 0;
    cpix = ppix = 0;
    run_count1 = run_count2 = 0;

    for (col=MAXCOL; col >=0; col--) {
        l_cpix = cpix;                    /* backup last pixel */
        l_ppix = ppix;
        cpix = image[i][col];             /* current pixel in current row */
        ppix = image[i+1][col];           /* current pixel in previous row */

        /* If an run starts in previous row, read the associated bracket
           marking from the table */
        if (START_P) {
            l_brkt[0] = brkt[0];
            l_brkt[1] = brkt[1];
            run_count2++;
            brkt[0] = BrktL[i+1][run_count2];
            brkt[1] = BrktR[i+1][run_count2];
        }
    }
}

```

```

/* if an run starts in current row, initial the entry of it in the table */
if (START_C) {
    run_count1++;
    BrktL[i][run_count1] = 0;
    BrktR[i][run_count1] = 0;
}

/* runs start in both current row and previous row simultaneously */
if ((START_P) && (START_C)) {
    switch (BRKT) {
        /* push a marked entry on stack1;
        push a new group entry on stack2. */
        case RIGHT:
        case CLOSE:
            sp1++;
            stack1[sp1][0] = stack1[sp1][1] = 1;
            sp3++;
            stack2[sp3][0] = stack2[sp3][1] = run_count1;
            break;

        case MID :
        case LEFT :
            /* expand the group on the top of stack2 at its right boundary */
            if (stack1[sp1][0]) {
                BrktL[i][stack2[sp3][0]] = 1;
                BrktR[i][run_count1] = 1;
                stack2[sp3][0] = run_count1;
            }
            /* push a new group entry on stack2 */
            else {
                sp3++;
                stack2[sp3][0] = stack2[sp3][1] = run_count1;
                if (BRKT == MID) {
                    stack1[sp1][0] = 1;
                }
            }
            break;
    }
}

/* an run starts in previous row, but no transition in current row */
else if ((START_P) && !(START_C) && !(END_C)) {
    if (!OVERLAP) {
        /* push an unmarked entry on stack1 */
        switch (BRKT) {
            case RIGHT:
            case CLOSE:
                sp1++;
                stack1[sp1][0] = 0;
                stack1[sp1][1] = 1;
                break;
        }
    } else {

```



```

switch (BRKT) {
    /* push a marked entry on stack1 */
    case RIGHT:
    case CLOSE:
        sp1++;
        stack1[sp1][0] = 1;
        if (!touch_p)
            stack1[sp1][1] = 1;
        else {
            if (l_brkt[0] == 1)
                stack1[sp1][1] = 0;
            else
                stack1[sp1][1] = stack2[sp3][2];
        } break;
    /* Combine two top groups of stack2 into one */
    case MID :
    case LEFT : if (stack1[sp1][0] && ((touch_p &&
        !l_brkt[0] && popped1) ||
        !touch_p)) {
        popped2[0] = stack2[sp3][0];
        popped2[1] = stack2[sp3][1];
        sp3--;
        BrktR[i][popped2[1]] = 1;
        BrktL[i][stack2[sp3][0]] = 1;
        stack2[sp3][0] = popped2[0];
    } break;
}

}

/* an run starts in current row, but no transition in previous row */
else if ((START_C) && !(START_P) && !(END_P)) {
    if (!OVERLAP) {
        /* push a new group entry on stack2 */
        sp3++;
        stack2[sp3][0] = stack2[sp3][1] = run_count1;
        stack2[sp3][2] = 1;
    } else {
        switch (BRKT) {
            case RIGHT:
            case CLOSE:
                /* mark the entry on the top of stack1;
                push a new group entry on stack2. */
                if (!touch_c) {
                    sp3++;
                    stack2[sp3][0] =
                    stack2[sp3][1] = run_count1;
                    stack2[sp3][2] = 1;
                    stack1[sp1][0] = 1;
                    stack1[sp1][1] = 1;
                }
                /* expand the group on the top of stack2 at its right boundary */
                else {

```

```

        BrktR[i][run_count1] = 1;
        BrktL[i][stack2[sp3][0]] = 1;
        stack2[sp3][0] = run_count1;
    }
    break;
case MID :
case LEFT :
    /* expand the group on the top of stack2 at its right boundary */
    if (touch_c) {
        BrktR[i][run_count1] = 1;
        BrktL[i][stack2[sp3][0]] = 1;
        stack2[sp3][0] = run_count1;
    } else {
        /* Expand the group on the top of stack2 at
           its right boundary */
        if (stack1[sp1][0]) {
            BrktR[i][run_count1] = 1;
            BrktL[i][stack2[sp3][0]] = 1;
            stack2[sp3][0] = run_count1;
        }
        /* push a new group entry on stack2 */
        else {
            sp3++;
            stack2[sp3][0] = run_count1;
            stack2[sp3][1] = run_count1;
            if (BRKT == MID){
                stack1[sp1][0] = 1;
            }
        }
    }
}

}

/* both runs in current row and previous row terminate simultaneously */
else if ((END_P) && (END_C)) {
    touch_c = touch_p = 0;

    /* If the group on the top of stack2 is finished, pop it off stack2. */
    switch (BRKT) {
    case CLOSE:
    case LEFT :
        if (stack1[sp1][1]) sp3--;
        popped1 = stack1[sp1--][1];
        break;
    }
}

/* the run in previous row terminates, but no transition in current row. */
else if ((END_P) && !(START_C) && !(END_C)) {
    if (!IN_CRUN) {
        /* pop the group on the top of stack2, if it is end. */
        switch (BRKT) {

```

```

    case CLOSE:
        if ((touch_c) && (stack1[sp1][1]))
            sp3--;
        popped1 = stack1[sp1--][1];
        break;
    case LEFT :
        if ((stack1[sp1][0] && stack1[sp1][1])
            || (touch_c && stack2[sp3][2]))
            sp3--;
        popped1 = stack1[sp1--][1];
        break;
    }
} else {
    touch_p = 1;
    switch (BRKT) {
        /* backup the auxillary flag, then pop stack1. */
        case CLOSE:
        case LEFT :
            stack2[sp3][2] = stack1[sp1][1];
            popped1 = stack1[sp1--][1];
            break;
    }
    touch_c = 0;
}

/* the run in current row terminates, but no transition in previous row. */
else if ((END_C) && !(START_P) && !(END_P)) {
    /* if the group on the top of stack2 is end, pop it off stack2. */
    if (!IN_PRUN) {
        if (!touch_p) {
            sp3--;
        } else {
            switch (BRKT) {
                case CLOSE:
                case LEFT :    if (stack2[sp3][2]) {
                                sp3--;
                                } break;
            }
        }
    } else {
        touch_c = 1;
    }
    touch_p = 0;
}

/* an run starts in previous row, and the run in current row terminates at the same time. */
else if ((START_P) && (END_C)) {
    /* if the group on the top of stack2 is end, pop it off. */
    if (!touch_p) {
        sp3--;
    } else {
        switch (BRKT) {
            case CLOSE:
            case LEFT :    if (stack2[sp3][2]) {

```

```

        sp3--;
        } break;
    }
}
switch (BRKT) {
    /* push an unmarked entry on stack1 */
    case RIGHT:
    case CLOSE:
        sp1++;
        stack1[sp1][0] = 0;
        stack1[sp1][1] = 1;
        break;
    }
    touch_p = touch_c = 0;
}

/* an run starts in current row, and the run in previous row terminates at the same time. */
else if ((START_C) && (END_P)) {
    switch (BRKT) {
        /* if the group on the top of stack2 is end, pop it off. */
        case CLOSE:
        case LEFT :    if ((touch_c) && (stack1[sp1][1])) {
                        sp3--;
                    }
                    popped1 = stack1[sp1--][1];
                    break;
        }
        /* push a new group entry o stack2 */
        sp3++;
        stack2[sp3][0] = stack2[sp3][1] = run_count1;
        stack2[sp3][2] = 1;
        touch_p = touch_c = 0;
    }
}
}

```

Sweep_of_Pass2(i)

```

Int    i;
{
    short  stack1[MAXRUN][2];          /* stack1 is for tracking brackets in previous row */
    Int    sp1;                        /* stack pointer for stack1 */

    Int    stack2[MAXRUN];              /* stack2 is for storing components numbers
                                        of runs in current row. */
    Int    sp2;

    Int    components_queue[Qlen];
    Int    col,code;
    Int    current_component;

    sp1 = sp2 = 0;
    cpix = ppix = 0;
    run_count1 = 0;
    for (col=MAXCOL; col >= 0; col--) {
        Lcpix = cpix;
        Lppix = ppix;
        cpix = image[i][col];
        ppix = image[i-1][col];

        /* if an run starts in previous row, increment queue_count2
           to point to the entry of queue containning the component number
           associated with this run. */
        If (START_P) {
            queue_count2 = ((queue_count2+1) % (Qlen));
        }

        /* if an run starts in current row, increment queue_count1 to
           allocate an entry in queue for this run. Read the bracket marking
           associated with this run from the table. */
        If (START_C) {
            queue_count1 = ((queue_count1+1) % (Qlen));
            run_count1++;
            brkt[0] = BrktL[i][run_count1];
            brkt[1] = BrktR[i][run_count1];
        }

        If ((START_P) && (START_C)) {
            /* Induce the component number from the contacted run in previous row */
            switch (BRKT) {
                case RIGHT:
                case CLOSE:
                    sp1++;
                    stack1[sp1][0] = components_queue[queue_count2];
                    stack1[sp1][1] = 1;
                    break;
                case LEFT :
                case MID :
                    If (!stack1[sp1][1]) {
                        stack1[sp1][0] = components_queue[queue_count2];
                        stack1[sp1][1] = 1;
                    }
            }
        }
    }
}

```

```

    }
        break;
    }
} else if ((START_P) && !(START_C) && !(END_C)) {
    /* Induce the component number from the contacted run in previous row */
    if ((OVERLAP) && (!stack1[sp1][1])) {
        stack1[sp1][0] = components_queue[queue_count2];
        stack1[sp1][1] = 1;
    }
} else if ((START_C) && !(START_P) && !(END_P)) {
    switch (BRKT) {
        case RIGHT:
        case CLOSE:
            /* set the component number to NULL temporarily */
            if (!OVERLAP) {
                sp1++;
                stack1[sp1][0] = stack1[sp1][1] = 0;
            }
            /* Induce the component number from previous row */
            else {
                sp1++;
                stack1[sp1][0] = components_queue[queue_count2];
                stack1[sp1][1] = 1;
            }
            break;
        case MID :
        case LEFT :
            /* Induce the component number from previous row */
            if ((OVERLAP) && (!stack1[sp1][1])) {
                stack1[sp1][0] = components_queue[queue_count2];
                stack1[sp1][1] = 1;
            }
            break;
    }
} else if ((END_P) && (END_C)) {
    /* save the component number for a finished group in current
       row into stack2 to be used in second sweep. */
    switch (BRKT) {
        case CLOSE:
        case LEFT :
            stack2[++sp2] = stack1[sp1--][0];
            break;
    }
} else if ((END_P) && !(START_C) && !(END_C)) {
    /* NULL */
} else if (((END_C) && !(START_P) && !(END_P)) ||
           ((START_P) && (END_C))) {
    switch (BRKT) {
        case CLOSE:
        case LEFT :
            /* save the component number of a finished group into stack2 */
            if (stack1[sp1][1])
                stack2[++sp2] = stack1[sp1--][0];
            /* If the finished group belongs to a new component, then
               assigne a new number to it and save in stack2. */

```

```

        else {
            stack2[++sp2] = component_No++;
            sp1--;
        } break;
    }
} else if ((START_C) && (END_P)) {
    /* set the component number to NULL temporarily */
    switch (BRKT) {
        case RIGHT:
        case CLOSE:
            sp1++;
            stack1[sp1][0] = stack1[sp1][1] = 0;
            break;
    }
}

sp1 = 0; cpix = 0;
current_component = 0;
queue_count2 = queue_count1;

for (col=0; col<=MAXCOL; col++) {
    l_cpix = cpix;
    cpix = image[i][col];

    if (START_C) {
        brkt[0] = BrktL[i][run_count1];
        brkt[1] = BrktR[i][run_count1];
        run_count1--;

        switch (BRKT) {
            case LEFT :    current_component = stack2[sp2--];
                            stack1[++sp1][0] = current_component;
                            break;
            case MID :     current_component = stack1[sp1][0];
                            break;
            case RIGHT:    current_component = stack1[sp1--][0];
                            break;
            case CLOSE:    current_component = stack2[sp2--];
                            break;
        }
        /* save the component number of current run into queue */
        components_queue[queue_count2] = current_component;
        queue_count2 = ((queue_count2-1+Qlen) % (Qlen));
    } else if (END_C) {
        current_component = 0;
    }

    /* map the component number into pseudo color, and store it
       into the destination image. */
    code = (current_component == 0) ? 6 : (c_id % 6);
    components[i][col] = colour[code];
}
}

```

Appendix.B

Process Description of The Algorithm in A Microparallel Hardware Design Language

B.1 Definitions of Variables and Flags

image_buffer(0..511,0..511);	<i>/* The image storage buffer is divided into two ranks, one for even rows and one for odd */</i>
Left_bracket_table(0..511,0..255);	<i>/* Table of left bracket bits */</i>
Right_bracket_table(0..511,0..255);	<i>/* Table of right bracket bits */</i>
Row_Count1;	<i>/* 9 bits: binary up-down counter */</i>
Row_Count2;	<i>/* 9 bits: Binary up-down counter */</i>
Column_Count;	<i>/* 9 bits: binary up-down counter */</i>
Bracket_Count1;	<i>/* 8 bits: up-down counter */</i>
Bracket_Count2;	<i>/* 8 bits: up-down counter */</i>
P1_Stack1(256,2);	<i>/* Pushdown stack holds two 1-bit fields; depth 256 */</i>
P1_Stack2(256,3);	<i>/* Pushdown stack holds three fields; depth 256 */</i>
P2_Stack1(256,2);	<i>/* Pushdown stack holds two fields; depth 256 */</i>
P2_Stack2(256,1);	<i>/* Pushdown stack holds one field; depth 256 */</i>
S1_popped(2);	<i>/* Last value popped from P1_Stack1 */</i>
S2_popped(3);	<i>/* Last value time popped from P1_Stack2 */</i>
Queue(0..512);	<i>/* Circular queue */</i>
Queue_Count1;	<i>/* 9 bits: counter pointing to front of queue */</i>
Queue_Count2;	<i>/* 9 bits: counter pointing to end of queue */</i>
CPIX;	<i>/* 1 bit: current pixel of current row */</i>
I_CPIX;	<i>/* 1 bit: previous pixel of current row */</i>
PPIX;	<i>/* 1 bit: current pixel of previous row */</i>
I_PPIX;	<i>/* 1 bit: previous pixel of previous row */</i>
brkt(2);	<i>/* 2 bits: current brackets */</i>
I_brkt(2);	<i>/* 2 bits: previous brackets */</i>
touch_c;	<i>/* 1 bit: flag used in PASS 1 */</i>
touch_p;	<i>/* 1 bit: flag used in PASS 1 */</i>
In_Down_load;	<i>/* flag: indicates down loading in progress */</i>
In_Pass1;	<i>/* flag: indicates Pass1 in progress */</i>
In_Pass2;	<i>/* flag: indicates Pass2 in progress */</i>
Start_pass1;	<i>/* flag: enables process Initialization_of_Sweep_of_Pass1 */</i>
Start_pass2;	<i>/* flag: enables process P2S1_Row_Initialization */</i>
Sweep2_of_Pass2_enable;	<i>/* flag: enables process P2S2_Row_Initialization */</i>


```

Start_Row_Sweep_of_Pass1;          /* flag: enables process Read_Pixel */
Start_Row_Sweep1_of_Pass2;         /* flag: enables process Read_Pixel */
Start_Row_Sweep2_of_Pass2;         /* flag: enables process Read_Pixel */
Next_Row_P1;                       /* flag: enables process Initialization_of_Sweep_of_Pixel */
Next_Row_P2;                       /* flag: enables process P2S1_Row_Initialization */
Next_Pixel_1;                      /* flag: enables process Read_Pixel */
Next_Pixel_2;                      /* flag: enables process Read_Pixel */
Next_Pixel_3;                      /* flag: enables process Read_Pixel */
P1_pixel_op_enable;                /* flag: enables process Pixel_Computation_of_Pass1 */
P2S1_pixel_op_enable;              /* flag: enables process Pixel_Computation_of_Sweep_of_Pass2 */
P2S2_pixel_op_enable;              /* flag: enables process Pixel_Computation_of_Sweep_of_Pass2 */

component_number;                  /* Next new component number */
current_component;                 /* component number of current scanned pixel */

```

B.2 Description of Primitive Operations

1. Assigning a value to a simple variable or indexed variable has obvious meaning.
2. Four stack operations are used:

```

push(stack_name, vector);          /* push a vector onto multi-field
                                   stack */

pop(stack_name);                   /* pop the top of a stack */

top(stack_name) = vector;          /* modify the top of a stack */

top(stack_name)[i] = variable;     /* modify a specific field of
                                   a stack */

```

3. Queue operations are treated as indexed accesses to an underlying array.

B.3 Processes

/ Initialize row counters for Pass 1 then start row sweeping process */*

Process PASS1_Initialization

```

If (Pass1 & !In_Down_Load & !In_Pass1 & !In_Pass2) then
    In_Pass1 = true;
    Row_Count1 = 511;
    Row_Count2 = 0;
    Start_Pass1 = true;
else
    Start_pass1 = false;
EndIf;

```

/ Terminate Pass 1 after all rows have been scanned */*

Process PASS1_Termination

```

if (In_Pass1 & Next_Row_P1 & Row_Count1 == 511) then
    In_Pass1 = false;
Endif;

```

/ Initialize column counter variables and flags at entrance of a row sweep
in Pass1 then enable reading pixel process */*

Process Initialization_of_Sweep_of_Pass1

```

if (Start_Pass1 | (Next_Row_P1 & Row_Count1 != 511)) then
    Next_Row_P1 = false;
    Column_Count = 511;
    reset(P1_stack1);
    reset(P1_stack2);
    CPIX = 0;
    PPIX = 0;
    touch_p = 0;
    touch_c = 0;
    Bracket_Count1 = 0;
    Bracket_Count2 = 0;
    Start_Row_Sweep_Pass1 = true;
else
    Start_row_Sweep_Pass1 = false;
Endif;

```

/ At the end of each sweep, update row counters, and start sweep on next row */*

Process End_of_Sweep_of_Pass1

```

if (Next_Pixel_1 & Column_Count == 511) then
    Row_Count1 --;
    Row_Count2 --;
    Next_Row_P1 = true;
Endif;

```

/ Load next pixels from current row and previous row simultaneously into registers CPIX
PPIX respectively, and old contents of CPIX and PPIX was backed into l_CPX and l_PPIX
respectively. If a run started in a previous row, the corresponding bracket marking
is loaded from bracket table. */*

Process Read_Pixel

/ In sweep 1 of pass 1:*

```

    Read pixels from two rows simultaneously from right to left.
    */
    If (Start_Row_Sweep_of_Pass1 | Next_Pixel_1 & Column_Count != 511) then
        Next_Pixel_1 = false;
        l_CPIX = CPIX;
        l_PPIX = PPIX;
        CPIX = image_buffer(Row_Count1,Column_Count);
        PPIX = image_buffer(Row_Count2,Column_Count);
        Column_Count --;

        If (PPIX=1 & l_PPIX=0) then
            l_brkt[left] = brkt[left];
            l_brkt[right] = brkt[right];
            Bracket_Count2 ++;
            brkt[left] = Left_bracket_table(Row_Count2,Bracket_Count2);
            brkt[right] = Right_bracket_table(Row_Count2,Bracket_Count2);
        EndIf;

        If (CPIX=1 & l_CPIX=0) then
            Bracket_Count1 ++;
            Left_bracket_table(Row_Count1,Bracket_Count1) = 0;
            Right_bracket_table(Row_Count1,Bracket_Count1) = 0;
        EndIf;

        P1_pixel_op_enable = true;

/* In sweep 1 of pass 2:
    Read pixels from two rows simultaneously from right to left.
    */
    else If (Start_Row_Sweep1_of_Pass2 | Next_Pixel_2 & Column_Count != 511) then
        Next_Pixel_2 = false;
        l_CPIX = CPIX;
        l_PPIX = PPIX;
        CPIX = image_buffer(Row_Count1,Column_Count);
        PPIX = image_buffer(Row_Count2,Column_Count);
        Column_Count --;

        If (PPIX=1 & l_PPIX=0) then
            Queue_Count2 ++;
        EndIf;

        If (CPIX=1 & l_CPIX=0) then
            Queue_Count1 ++;
            Bracket_Count2 ++;
            brkt[left] = Left_bracket_table(Row_Count1,Bracket_Count2);
            brkt[right] = Right_bracket_table(Row_Count1,Bracket_Count2);
        EndIf;

        P2S1_pixel_op_enable = true;

/* In sweep 2 of pass2:
    Read pixels from two rows simultaneously from left to right.
    */

```

```

else If (Start_Row_Sweep2_of_Pass2 | Next_Pixel_3 & Column_Count != 0) then
    Start_Row_Sweep2_of_Pass2 = false;
    Next_Pixel_3 = false;
    l_CPIX = CPIX;
    CPIX = image_buffer(Row_Count1,Column_Count);
    Column_Count ++;

    If (CPIX=1 & l_CPIX=0) then
        brkt[left] = Left_bracket_table(Row_Count1,Bracket_Count2);
        brkt[right] = Right_bracket_table(Row_Count1,Bracket_Count2);
        Bracket_Count2 --;
    EndIf;

    P2S2_pixel_op_enable = true;
EndIf;

```

/ this is the main computation process of Pass1. In different cases of combinational conditions appropriate manipulation are carried out on two stacks and bracket table. */*

Process Pixel_Computation_of_Pass1

```

If (P1_pixel_op_enable) then
    P1_pixel_op_enable = false;

    case of

        /* Start a run on both current and previous rows */
        (PPIX=1 & l_PPIX=0 & CPIX=1 && l_CPIX=0):
            case of
                (brkt[right]=0):
                    push(P1_Stack1,(1,1));
                    push(P1_Stack2,(bracket_Count1,bracket_Count1));

                (brkt[right]=1):
                    If (top(P1_Stack1)[0]) then
                        Left_bracket_table(Row_Count1,top(P1_Stack2)[0])=1;
                        Right_bracket_table(Row_Count1,Bracket_Count1)=1;
                    else
                        push(P1_Stack2,Bracket_Count1,Bracket_Count1);
                        If (brkt[left]=1) then
                            top(P1_Stack1)[0] = 1;
                        EndIf;
                    EndIf;
            Endcase;

        Endcase;

        /* Only start a new run in previous row. There is no
        transition on current row. */
        (PPIX=1 & l_PPIX=0 & !(CPIX xor l_CPIX)):
            If !(CPIX & PPIX) then
                case of

```

```

(brkt[right]=0):
    push(P1_Stack1,(0,1));
    Endcase;
else case of
    (brkt[right]=0):
        push(P1_Stack1,(1, !touch_p | touch_p &
            !brkt[left]=0 & top(P1_Stack2)[2]));
    (brkt[right]=1):
        if (top(P1_Stack1)[0] & (touch_p & !brkt[left]
            & S1_popped[1] | !touch) then
            S2_popped = pop(P1_Stack2);
            Rightbracket_table(Row_Count1,S2_popped[1]) = 1;
            left_bracket_table(Row_Count1,top(P1_Stack2)[0]) = 1;
            top(P1_Stack2)[0] = S2_popped[0]
        Endif;
    Endcase;
Endif;

/* Start a new run in current row. There is no transition
on previous row. */
(CPIX=1 & !CPIX=0 & !(PPIX xor !PPIX)):
    if !(CPIX & PPIX) then
        push(P1_Stack2,(bracket_Count1,bracket_Count1,1);
    else
        case of
            (brkt[right]=0):
                if (!touch_c) then
                    push(bracket_Count1,Bracket_Count1,1);
                    top(P1_Stack1)=(1,1);
                else
                    Left_bracket_table(Row_Count1,top(P1_Stack2)[0]) = 1;
                    Right_bracket_table(Row_Count1,Bracket_Count1) = 1;
                    top(P1_Stack2)[0] = Bracket_Count1;
                Endif;
            (brkt[right]=1):
                if (touch_c | !touch_c & top(P1_Stack1)[0]) then
                    Right_bracket_table(Row_Count1,Bracket_Count1) = 1;
                    Left_bracket_table(Row_Count1,top(P1_Stack2)[0]) = 1;
                    top(P1_Stack2)[0] = Bracket_Count1;
                else if (!touch_c & !top(P1_Stack1)[0]) then
                    push(P1_Stack2,Bracket_Count1,Bracket_Count1);
                    if (brkt[left]=1) then
                        top(P1_Stack1)[0] = 1;
                    Endif;
                Endif;
        Endcase;
    Endif;

/* Reached the end of a current run in both previous row
and current row. */
(PPIX=0 & !PPIX=1 & CPIX=0 & !CPIX=1):

```

```

touch_c = 0;
touch_p = 0;
case of
(brkt[left]=0):
    if (top(P1_Stack1)[1]) pop(P1_Stack2);
    S1_popped = pop(P1_Stack1);
Endcase;

/* Reached the end of a run in previous row. But there is
   no transition on current row. */
(PPIX=0 & !PPIX=1 & !(CPIX xor !CPIX)):
    if (!CPIX) then
        case of
        (brkt[left]=0 & brkt[right]=0):
            if (touch_c & top(P1_Stack1)[1]) then
                pop(P1_Stack2);
            Endif;
            S1_popped = pop(P1_Stack1);

        (brkt[left]=0 & brkt[right]=1):
            if (top(P1_Stack1)[0] & top(P1_Stack1)[1] |
                touch_c & top(P1_Stack2)[2]) then
                pop(P1_Stack2);
            Endif;
            S1_popped = pop(P1_Stack1);
        Endcase;
    else
        touch_p = 1;
        case of
        (brkt[left] = 0):
            top(P1_Stack2)[2] = top(P1_Stack1)[1];
            S1_popped = pop(P1_Stack1);
        Endcase;

    Endif;
    touch_c = 0;

/* Reached the end of a run in current row. But there is
   no transition on previous row. */
(CPIX=0 & !CPIX=1 & !(PPIX xor !PPIX)):
    if (!PPIX) then
        if (!touch_p | touch_p & brkt[left]=0 & top(P1_Stack2)[2]) then
            pop(P1_Stack2);
        Endif;
    else
        touch_c = 1;
    Endif;
    touch_p = 0;

/* Start a new run in previous row and reach the end of the
   current run in current row simultaneously. */
(PPIX=1 & !PPIX=0 & CPIX=0 & !CPIX=1):
    if (!touch_p | touch_p & brkt[left]=0 & top(P1_Stack2)[2]) then

```

```

        pop(P1_Stack2);
    Endif;
    If (brkt[right]=0) then
        push(P1_Stack1,(0,1));
    Endif;
    touch_p = 0;
    touch_c = 0;

    /* Start a new run in current row and reach the end of the
       current run in previous row simultaneously. */
    (CPIX=1 & L_CPIX=0 & PPIX=0 & L_PPIX=1):
        If (brkt[left]=0 & touch_c & top(P1_Stack1)[1]) then
            pop(P1_Stack2);
        Endif;
        push(P1_Stack2,Bracket_Count1,Bracket_Count1,1);
        touch_p = 0;
        touch_c = 0;

    Endcase;

    Next_Pixel_1 = true;
Endif;

/* Initialize row counters, queue counters and set next component number
   to 1, then start first sweep of row 1 */

Process PASS2_Initialization

If (Pass2 & !In_Down_Load & !In_Pass1 & !In_Pass2) then
    In_Pass2 = true;
    Row_Count1 = 0;
    Row_Count2 = 511;
    Queue_Count1 = 0;
    Queue_Count2 = 0;
    component_number = 1;
    Start_Row_Sweep2_of_Pass2 = true;
else
    Start_Row_Sweep2_of_Pass2 = false;
Endif;

/* Terminate pass 2 after all rows have been scanned */

Process PASS2_Termination

If (In_Pass2 & Next_Row_P2 & Row_Count1=0) then
    In_Pass2 = false;
Endif;

```

/ Initialize column counter, stacks and other variables for the first sweep of a row in pass 2; then enable process Read_Pixel to load next pixels from current row and previous row */*

Process P2S1_Row_Initialization

```

If (Start_Pass2 | (Next_Row_P2 & Row_Count1 != 511)) then
    Next_Row_P2 = false;
    Column_Count = 511;
    reset(P2_stack1);
    reset(P2_stack2);
    CPIX = 0;
    PPIX = 0;
    Bracket_Count2 = 0;
    Start_Row_Sweep1_of_Pass2 = true;
else
    Start_Row_Sweep1_of_Pass2 = false;
EndIf;

```

/ After the first sweep, from right to left, reaches the end of a row, second sweep, from left to right, is enabled */*

Process End_of_Sweep1_of_Pass2

```

If (Next_Pixel_2 & Column_Count=511) then
    Sweep2_of_Pass2_enable = true;
EndIf;

```

/ This is main computation process in first sweep of a row in pass 2 */*

Process Pixel_Computation_of_Sweep1_of_Pass2

```

If (P1S1_pixel_op_enable) then
    P1S1_pixel_op_enable = false;

    case of

        /* Start a new run on both previous row and current row
           simultaneously. */
        (PPIX=1 & !PPIX=0 & CPIX=1 && !CPIX=0):
            case of
                (brkt[right]=0):
                    push(P2_Stack1,(Queue(Queue_Count2),1));
                (brkt[right]=1):
                    If !top(P2_Stack1)[1] then
                        push(P2_Stack1,(Queue(Queue_Count2),1));
                    EndIf;
            Endcase;
    Endcase;

```



```

/* Start a new run in previous row. But there is no
transition on current row. */
(PPIX=1 & L_PPIX=0 & !(CPIX xor L_CPIX)):
    if (CPIX & PPIX & !top(P2_Stack1)[1]) then
        top(P2_Stack1) = (Queue(Queue_Count2),1);
    Endif;

/* Start a new run in current row. But there is no
transition on previous row. */
(CPIX=1 & L_CPIX=0 & !(PPIX xor L_PPIX)):
    case of
        (brkt[right]=0):
            if (CPIX & PPIX) then
                push(P2_Stack(0,0));
            else
                push(P2_Stack1,(Queue(Queue_Count2),1));
            Endif;
        (brkt[right]=1):
            if (CPIX & PPIX & !top(P2_Stack1)[1]) then
                top(P2_Stack1)[1] = 1;
            Endif;
    Endcase;

/* Reach the end of the current run on both previous
row and current row simultaneously. */
(PPIX=0 & L_PPIX=1 & CPIX=0 & L_CPIX=1):
    if (brkt[left]=0) then
        push(P2_Stack2,pop(P2_Stack1)[0]);
    Endif;

/* Reach the end of current run in previous row. But
there is no transition on current row. */
(PPIX=0 & L_PPIX=1 & !(CPIX xor L_CPIX)):
    NOP;

/* Reach the end of current run in current row and
there is no transition or start a new run in
previous row. */
(CPIX=0 & L_CPIX=1 & !(PPIX xor L_PPIX)):
(PPIX=1 & L_PPIX=0 & CPIX=0 & L_CPIX=1):
    case of
        (brkt[left]=0):
            if (top(P2_Stack1)[1]) then
                push(P2_Stack2,pop(P2_Stack1)[0]);
            else
                push(P2_Stack2,component_number);
                pop(P2_Stack1);
                component_number ++;
            Endif;
    Endcase;

/* Start a new run in current row and reach the end
of current run in previous row. */

```

```

(CPIX=1 & 1_CPIX=0 & PPIX=0 & 1_PPIX=1):
    case of
        (brkt[right]=0):
            push(P2_Satack1,(0,0));
        Endcase;

    Endcase;

    Next_Pixel_2 = true;
Endif;

/* Initialize column counter, stack, and other variables for second
   sweep of a row in pass 2; then enable process Read_Pixel */

Process P2S2_Row_Initialization

If (Sweep2_of_Pass2_enable) then
    Sweep2_of_Pass2_enable = false;
    Column_Count = 0;
    reset(P2_stack1);
    CPIX=0;
    current_component = 0;
    Queue_Count2 = Queue_Count1;
    Start_Row_Sweep2_of_Pass2 = true;
endif;

/* After the second sweep of a row is finished, row-counters are incremented
   by one for next row. */

Process End_of_Sweep2_of_Pass2

If (Next_Pixel_3 & Column_Count=0) then
    Row_Count1 ++;
    Row_Count2 ++;
    Next_Row_P2 = true;
Endif;

/* This is main computation process in second sweep of a row in Pass 2 */

Process Pixel_Computation_of_Sweep2_of_Pass2

If (P1S2_pixel_op_enable) then
    P1S2_pixel_op_enable = false;

    case of

        /* Start a new run in current row. */

```

```

(CPIX=1 & !CPIX=0):
    case of
        (brkt[left]=0 & brkt[right]=1):
            current_component = pop(P2_Stack2);
            push(P2_Stack1,current_component);
        (brkt[left]=1 & brkt[right]=1):
            current_component = top(P2_Stack1);
        (brkt[left]=1 & brkt[right]=0):
            current_component = pop(P2_Stack1);
        (brkt[left]=0 & brkt[right]=0):
            current_component = pop(P2_Stack2);
    Endcase;

    Queue(Queue_Count2) = current_component;
    Queue_Count2 ++;

    /* Reached the end of current run in current row. */
    (CPIX=0 & !CPIX=1):
        current_component = 0;

    Endcase;
    output(current_component);

    Next_Pixel_3 = true;
Endif;

```


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